

REPORT FROM THE SCHOOL OF EXPERIENCE:

Lessons-Learned on NASA's EOS/ICESat Mission^{1,2}

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Abstract—NASA's Earth Observing System (EOS) Ice, Cloud, and Land Elevation Satellite (ICESat) mission was one of the first missions under Goddard Space Flight Center's (then-) new Rapid Spacecraft Development Office. This paper explores the lessons-learned under the ICESat successful implementation and launch, focusing on four areas: Procurement, Management, Technical, and Launch and Early Operations. Each of these areas is explored in a practical perspective of communication, the viewpoint of the players, and the interactions among the organizations. Conclusions and lessons-learned are summarized in the final section.

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1. BACKGROUND

Goddard's Rapid Spacecraft Development Office (RSDO) was conceived to shorten the amount of runway time needed for a spacecraft contract to get through the procurement cycle, and at the same time simplify the post-award management burden. The goal of the first RSDO contract (or *Rapid I*, which has since evolved into *Rapid II*) was to competitively grant *core* contracts to a pool of qualified vendors for specific spacecraft (the *catalog*), and then quickly arrange match-ups ("Delivery Orders") between catalog items and mission payloads.

By the time of the formal kick-off for the ICESat mission in 1997 there had been almost 5,000 objects launched into orbit. After a campaign as extensive as that the aerospace industry had accrued a correspondingly massive infrastructure of established, traditional, tried-and-true procurement and management methods and standards. The RSDO concept challenged many of these methods and standards with the *Catalog* approach available for any Government mission. (Non-Government users can access RSDO as well if they can identify a Government representative to manage the contract).

The following sections describe how well or ill the Rapid Spacecraft worked for ICESat. The lessons-learned are discussed in the areas of procurement, management, technical, and launch and early operations.

2. PROCUREMENT

Even though it was only the second mission through the RSDO process, the procurement worked surprisingly well. There were no unusual rough spots or awkward points in the whole cycle – an indication that the preparatory RSDO work for the *core* contract had been particularly well thought-out. Communication between the contracting office and the project office, and between the contracting office and the Offerors was well facilitated under RSDO. Specific ICESat lessons-learned are pointed out in the following sections for the procurement cycle, contract paperwork, team pre-conceptions, and of course, the unknowns.

The success of the ICESat procurement was largely due to the expertise and dedication of the RSDO contracting officer, Ms. S. Collignon. The successful execution of the subsequent delivery order was dependent on the wisdom, integrity, and unfailing guidance of the late Linda Kelley, contracting officer for the ICESat mission.

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² IEEEAC paper #1169, Version 4, Updated November 10, 2003

Procurement Cycle

The standard competitive spacecraft procurement at the Goddard Space Flight Center (GSFC) takes about 190 days[1] from releasing the Request for Proposal to Award, as shown in Figure 1. Although there were still a few minor RSDO bugs to be worked out, the ICESat process only took 87 days, from mid-November through early February (including yuletide), about half the standard duration.

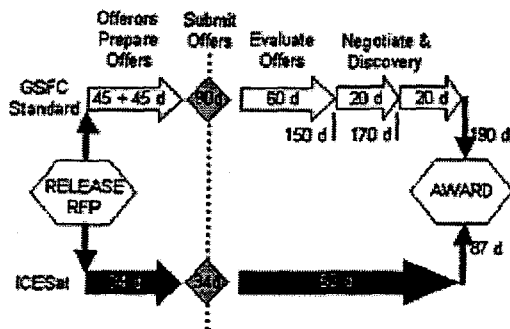


Figure 1. Standard vs. ICESat Procurement Time

The solicitation and evaluation times were shortened largely because each of the vendor's *catalog* spacecraft had already been reviewed in detail for the original RSDO core contract award, which meant there was a resident team of Goddard experts on-hand, fresh from that experience who needed no learning curve and were ready to review each ICESat offer for mission specifics. Furthermore, the offers were also identically formatted which simplified the review. This meant the viewpoint of all the players, Offerors and reviewers, was uniform and standard at the outset. Focusing on mission-uniques meant the evaluation criteria were few: a prioritized list of only the major mission requirements which was easily mapped to each vendor's offer. Lesser factors common to all the offers such as propulsion, communication, and power needed only to be confirmed as unchanged from the core offer and hence, did not need in-depth analysis.

Paperwork

Another benefit of the RSDO concept was that the mass of paperwork to document the mission was minimal; ICESat had only eighteen contract data items, compared with cost-type procurements which typically have at least 50 or more items. Beyond just technical documentation, the fixed-price performance base payment schedule also meant less administrative deliverables as well. For example, there were no monthly and quarterly cost reporting (NASA Form 533s) to regularly review and file.

Preconceptions

Over the life of the contract team preconceptions had to

be consistently overcome. The novelty of the RSDO concept had to be repeatedly reinforced among the Government team members who were more used to the traditional exhaustive contract details of staffing and skill levels, task definitions, design minutiae, and other material that was just not relevant to a performance-based effort. *How* was less important than *did it work*? This was achieved by keeping the performance issues at the fore during weekly telecons and regular management briefings. When interesting side paths peripheral to the core performance were pursued, no matter how fascinating, the team was reminded of the agreed performance baseline.

Unknowns

The RSDO framework does not handle unknowns like schedule uncertainties very well. For example, ICESat saw three six-month blocks of schedule delay due to late Government-Furnished Equipment (GFE). This could not be anticipated in the original request for offer, and so had to be managed as directed changes each time the schedule slipped. It required close coordination with the procurement office, the legal office, and the contractor to define the change dates with confidence, to establish new and repeat tasks for risk reduction, or sometimes to bite the bullet and reduce staff during the delay. Each of these situations paved new ground in the RSDO arena, but each was also successfully addressed in the end (although a cost-plus task would have been a lot easier).

3. MANAGEMENT

RSDO worked extremely well for managing the ICESat implementation. Some of the management lessons-learned noted here are in staffing, furnishing equipment, standardization, and milestone management.

Staffing

In the area of staffing alone, the performance-based contract required less support for monitoring and reporting contract performance than does the typical Goddard project. Project teams for a mission the size of ICESat at Goddard can range in excess of 50 people: the core senior staff of four or five, a few administrative types, and then specialists for each of the critical functional and interface areas to oversee the contractor's work. Table 1 shows the typical GSFC staffing versus how ICESat was staffed. Due to the performance-based milestones, comprehensive oversight of all the contractor detailed activities was not necessary, while specialists from the Instrumentor staff were selectively retained as-needed for consulting and to maintain the Project's insight into mission-critical spacecraft areas such as orbit determination, attitude control, and thermal management. This support was usually used to support major reviews.

Table 1. Typical Project vs. ICESat Staffing

TYPICAL PROJECT STAFFING	ICESat STAFFING
Project Manager	✓
Deputy Project Manager	✓
Deputy Project Mgr/Resources	✓
Administration	✓
Support Specialist	✓
Resource Analyst	✓
Observatory Manager	✓
Systems Engineer	✓
Systems Engineering Support	✓
Mission Operations	✓
Flight Operations	✓
Software Systems	✓
Launch Vehicle Interface	✓
Flight/Quality Assurance	✓
Safety	✓
Financial Manager	None
Instrument Manager	(Instrumentor)
Command & Data Handling	As needed
Communication	As needed
EEE Parts	As needed
Electrical Power & Distribution	As needed
Guidance, Navigation & Control	As needed
Integration & Test	As needed
IV&V (software)	As needed
Propulsion	As needed
Structure & Mechanisms	As needed
Thermal	As needed

Because of the difference between managing fixed-price and cost-plus contracts, it was vital to develop and maintain a good relationship with the contracting officer and the resource (or financial) manager, as well as with their counterparts on the contractor side.

Good communication between key players in the organizations keeps management aware of programmatic and legal issues before they become problems. Daily talks between the spacecraft manager and developer, between the systems engineers on both sides, and between technical leads, as well as the weekly team meetings, let problems get solved at the lowest level before they became show-stoppers.

Furnishing Equipment

Under performance-based contracting, it is better to never provide as Government-Furnished (GF) equipment or services, anything the prime could get on its own (ICESat had more than 29 GF line items). GF puts the Government squarely in the procurement and performance chain, with maximum exposure and liability. If the item is late, if it fails to perform, if there are access limits due to

proprietary constraints, if there is missing or inadequate documentation, maintenance, repair, updates, whatever, it all falls right in you're the Government's lap. Even if the markup is 200% or more to have the contractor procure the item, it is well worth it to get the Project Office out of the loop.

Among the ICESat GFE was the Global Positioning System (GPS) receivers and antennas, the spacecraft gyroscope, and star trackers on the instrument. Defining the interfaces, arranging delivery, assuring performance, documenting exceptions, all became major headaches that could have been avoided by including the procurement of the items in the scope of the delivery order.

Standardization

If your office, the contracts office, all the support organizations, and all the contractors use the same versions of word processing, presentation, and spreadsheet applications, you are guaranteed to still have translation problems that turn math and Greek symbols into gibberish. Retain a hard copy of your original text and reserve an extra day to confirm and correct the receiver's copy, if needed. The interaction among organizations facilitated this for ICESat after it was discovered that all the Greek and mathematical symbols in the request for offer had been transformed upon receipt into smiley faces, pointing hands, and other miscellaneous *Wingdings*.

If the contractor's embedded processes for quality assurance, anomaly tracking, parts control, etc., work to the RSDO standards, use them instead of your in-house process. The efficiency and effectiveness is worth any translation or accommodation effort.[2] ICESat used the contractor's File Transfer Protocol (FTP) site to maintain the engineering studies and contract data items, so the Project Office did not have all the worries on proprietary restrictions and international traffic in arms regulation. The contractor's internal anomaly reporting system was also evaluated and found to be comparable to Goddard's, so the contractor's system was used.

Every Project needs a digital camera – a web-accessible picture is worth a thousand meetings. There is no limit to the advantage a close-up of a solder joint, broken wire, connector, finished assembly, etc. can provide to solve problems or punch-up a status briefing.

Milestones

This first step in management by milestone is to make sure there are clear and unambiguous performance criteria defined for each milestone in the request for offer. For ICESat, most of the benchmark set defined at delivery order award worked well for the life of the contract.

Many other milestones were added over the course of time to include contract changes and amendments, but some six months before launch the requirements for the sign-off milestone, on-orbit acceptance, were found to be problematic. Because of the four years of trust and communication that had grown over the life of the delivery order, both Government and contractor text was offered up, evaluated, negotiated, and quickly agreed to. The milestone was re-defined prior to launch, and served well as the defining framework for accepting the successful mission after launch (discussed later in this paper).

Do not base performance milestone payment criteria on external events beyond the contractor's control, particularly Government-furnished items, Project review and approval, or Instrumentor information. When the delivery of the science instrument was delayed, the Government had to waive some of the criteria for Instrument Integration Readiness and pay the milestone anyway because our part of the deal was late.

Never hesitate to withhold a progress payment if a performance milestone is not met to your satisfaction[2]; the contractor's corrective action will be incredibly swift. It is an excellent tool to ensure actions do not linger but get closed-out efficiently. If a payment invoice was rejected, the contractor was informed immediately so they could start fixing the problem and minimize the delay, without waiting for official notice. While infrequent, this did happen a few times on ICESat, and was very effective when it did occur.

4. TECHNICAL

RSDO worked fairly well for the technical execution of ICESat, but fixed-price is not a friendly environment when unknowns are the norm. This issue was most evident in the technical arena. The lessons-learned discussed below include Requirements, Integration and Test (I&T), and Mission Operations.

Requirements

All the contractor provides under fixed-price performance is a demonstration or test of performance against the baseline requirements. So keep these two points in mind:

- A requirement that is not tested is a goal.
- There is no recourse if a contractor fails to meet a goal.

Therefore, make sure all requirements are testable, that all requirements are tested, and that all tests can be traced back to requirements. ICESat had an extensive traceability matrix, which the spacecraft insisted upon, to accomplish this.

Under the original RSDO (*Rapid I*) Statement of Work (SOW) there is a task category called "Special Studies" (now called "Task Pool" under *Rapid II*) which is an excellent way to get the contractor to address all the technical areas that weren't included in the SOW in the first place. ICESat had more than 25 special studies over three years covering topics such as antenna multipath, agile spacecraft pointing, payload mass simulator, assessment of the reaction wheel sizing, and so on. It is crucial to make it very plain right away that the contractor does not see "Special Studies" as a way to "get well" for schedule or price mistakes in the proposal. ICESat had no problem in this area – all technical studies were promptly defined and executed.

The science instrument on ICESat, the Geoscience Laser Altimetry System (GLAS), did not have mature interfaces and proven procedures at the time of the RSDO spacecraft award, so there were many unplanned technical issues which took additional time to resolve during the spacecraft build. A mature payload package is a better fit for RSDO, in order that the Instrumentor avoid throwing instrument development problems "over the fence" to the spacecraft for solution. Constant vigilance on ICESat kept this to a minor and manageable concern.

Integration and Test

Fixed-price works great for the definition and implementation phases, however, it is very inappropriate for I&T. The contractor has to accept fixed price for high schedule risk (integrating an unknown instrument) – which means any necessary adjustments become very costly. Because of this, this phase of the development requires more management attention than any other.

Significant risk reducers for I&T include using:

- A spacecraft simulator (including engineering support) to verify the instrument interface prior to flight hardware delivery.
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- A master gage/drill template to assure mechanical interfacing by both sides of the interface.

For ICESat, mostly due to poor communication among the players during requirements definition, the simulators never worked to each user's expectations. Nonetheless, every time the limited functionality was exercised between the flight hardware and the simulator, an interface problem was revealed in time to correct the flight unit. As a result, after the flawless mechanical integration shown in

Figure 2, the electrical integration successfully completed in less than a day.

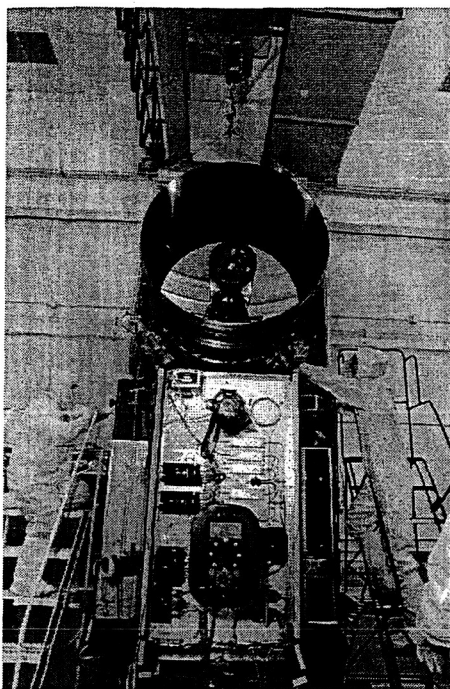


Figure 2. ICESat in I&T [3]

Without simulators, additional months of work are needed up front for troubleshooting and corrections after the instrument is delivered. It is reasonable to expect as much as half of the test procedures, simulations, and Ground Support Equipment (GSE) will have errors on first use. [2]

Fixed-price means there can be tension at the test execution level as to who will be the first to call a delay. It is best to remove cost and schedule concerns from day-to-day decision making among the test conductors as much as you possibly can. Maintain a strong continuous personal presence throughout System I&T to serve as the "honest broker" between organizations and let the as-planned I&T flow support the work to be done.[4] For ICESat, a log was kept and updated daily by the spacecraft and Project managers to account for the day's progress – noting whether additional time was spent for the spacecraft, instrument, or both. Then, when I&T was completed, the daily I&T records were racked-up to see if the overall schedule performance was within plan, and if not, how much price to allocate to the instrument or to the spacecraft.

Gather, plot, and trend data throughout the I&T campaign. This will be the performance baseline for analyzing all on-orbit anomalies, so the more information the better. Make sure to record the test conditions and configuration, the procedure versions, and all the test parameters. Many quirks and surprises on ICESat became typified and standardized for flight operations by tracking and

understanding their occurrence during I&T.

Mission Operations

To gain confidence in the mission operations capabilities, and to make sure there are not any latent timing problems hidden in the software, take the time to run "day-in-the-life" and extended duration simulations (e.g. 24/7), with the mission operators in support.[4] This way you buzz-out the system hardware, software, and staff while there is still time to address problems. ICESat ran an 8-day exercise that made us much more confident of our ability to operate post-launch, including all the clock creeps among the star trackers, data bus timing, and instrument and spacecraft clocks.

Allow the mission operations team continuous access to all testing activities.[4] This exercises the communication link, verifies the procedures, and builds confidence among the operations team. Make all the spacecraft and satellite test data available to the mission ops team for scenario development, procedure tests, etc. Encourage the use of the same systems and displays for operations and implementation (i.e. "Test it as you fly it, fly it as you test it"). ICESat's mission operations team was on-line for all spacecraft and mission testing, whenever they wanted to monitor activities.

Demonstrate every potential code load during I&T using the flight command and telemetry system.[4] This is particularly necessary if a unit vendor is absolutely certain none of his units has ever needed an on-orbit refresh in the entire history of the company. That unit will almost certainly be the first one to need a software patch or even a complete upload after launch. This happened on ICESat when a mature, proven product with extensive flight history had performance trouble related to a minor mission-unique hardware change that after launch was found to affect its performance in certain orbits and required a software change to fix it.

Mission rehearsals with simulated anomalies are a must to test the contingency flows and the operations team proficiency.[4] These need to be set up and run by very experienced teams, particularly teams independent from the mission in question. This reveals weak spots in the overall functional understanding, and really stresses the environment. The ICESat rehearsals ran for days, 24 hours without stop, with merciless clip-board wielding test team members roving among the operators and engineers recording performance and deficiencies.

5. LAUNCH & EARLY OPERATIONS

In the precise, business-like world of launch vehicles, RSDO worked very well. The launch environment is very well defined, with a lot of confidence and experience in the necessary steps and the execution plan.

Launch Support

The standard RSDO delivery order recommends a pre-priced one-month launch slip built in to the contract, although that can be tailored to fit the particular mission and launch vehicle. For ICESat's launch on Boeing's workhorse Delta II, one month was sufficient.

When you hand-over to the launch provider, it is no longer your system. You have now been relegated to "payload" status, and the mission focus is on safety, efficiency, countdown, and only then on accommodating your needs, whenever possible. Make sure your GSE and flight hardware can safely accommodate both momentary and lengthy power and communication interruptions at the pad. Make sure the last known configuration is always logged, and at restart automatically run a compliance comparison with the current configuration. During the launch rehearsal, with all the 80-odd consoles fully staffed and actively participating in the countdown, the south section of Vandenberg lost power and all communication and telemetry monitoring was lost. Fortunately, the GSE at the launch tower froze pre-flight operations and kept telemetry status static until power was restored.

Once your satellite is lifted on top of the rocket, you lose all control of the schedule – it is now up to the rocketeers. Include launch support time in your baseline for the "not-needed" activities like battery re-conditioning and general cleaning. A back-up detection module on the rocket was revealed to have had suspicious performance in earlier tests, and a two-week launch hold was declared. This put ICESat outside the recommended battery state-of-charge, and required reconditioning the batteries over the New Year. While it had never been rehearsed, the process of toting battery regulators up the tower, connecting coolers, and monitoring from the base, went right according to plan due to the diligence and expertise of the spacecraft contractor.

On-Orbit Acceptance

Long before launch, back in the initial request for offer, have clear and unambiguous performance requirements baselined for mission acceptance. Particularly performance requirements that can be clearly and unambiguously defined by telemetry (and demonstrated during I&T). As discussed earlier, these requirements were refined in the last year of the implementation, but demonstrating that the expected telemetry would document the required parameters was done in mission rehearsals, and verified after launch as much as needed to satisfy the Government.

With a customer anxious to take over the mission and a

contractor eager for the last milestone payment, this is not the time for open-ended discussions on differences in opinion.

6. CONCLUSIONS/LESSONS LEARNED

NASA's RSDO concept works well for missions with mature payloads (well-defined interfaces and functions), whose management keeps the following points in mind:

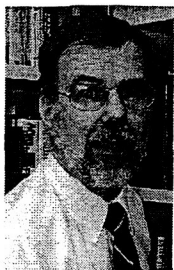
1. Keep Government-furnished items to the minimum.
2. Read and memorize lesson Number 1.
3. Contractors have no mercy. This means your statement of work should include all the info or data you really need, or think you really need, for the life of the contract – you may not get anything else. (But don't go overboard.)
4. RSDO will shorten the procurement cycle and reduce lifetime paperwork, if you know what you want to buy.
5. Changing requirements and loose schedule are not good for the fixed-price environment. Hold the Instrumentor to strict documentation and performance requirements during development. The Instrumentor's problems are the Instrumentor's problems.
6. A performance-based contract requires clear and unambiguous milestone payment criteria, which the contractor can meet without outside help.
7. The RSDO "Special Studies" (now called the "Task Pool" under Rapid II) are an excellent way to analyze and define changes and address new situations, as long as the contractor does not see them as a way to "get well".
8. Integration and test should proceed with the test conductors isolated from the schedule and cost accounting. Keep track of accounting separately with management, and do a rack-up after testing is done.
9. If you have to delay the spacecraft schedule, mission operations activities like day-in-the-life and long duration tests are excellent gap fillers.
10. Use the contractor's internal processes wherever possible, as long as they meet the performance requirements.

REFERENCES

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BIOGRAPHY

Bill Anselm has been an aerospace systems engineer and



manager for eighteen years. For the past thirteen years he has been helping NASA develop spacecraft and instruments, particularly for Earth- (NPP and EOS/ICESat) and Space- (ISTP/Wind & Polar) Science missions. Prior to that, he has led space communication development for DoD, developed world-wide automated systems to track sensitive equipment,

produced COMSEC gear, and managed labs for cardiovascular and psycho-acoustic research. He earned a BSEE from Syracuse University, and a Master of Arts in Business from Central Michigan University.